Phycologia

ISSN: 0031-8884 (Print) 2330-2968 (Online) Journal homepage: https://www.tandfonline.com/loi/uphy20

Phyconomy: the extensive cultivation of seaweeds, their sustainability and economic value, with particular reference to important lessons to be learned and transferred from the practice of eucheumatoid farming

Anicia Q. Hurtado, Iain C. Neish & Alan T. Critchley

PHYCOLOGIA
2019, VOL. 58, NO. 5, 472–483
https://doi.org/10.1080/00318884.2019.1625632

Phyconomy: the extensive cultivation of seaweeds, their sustainability and economic value, with particular reference to important lessons to be learned and transferred from the practice of eucheumatoid farming

Anicia Q. Hurtado[1], Iain C. Neish[2], and Alan T. Critchley[3]

[1]Aquaculture Department, Integrated Services for the Development of Aquaculture and Fisheries (ISDA) Inc, Iloilo City, 5000, Philippines
[2]PT Sea Six Energy Indonesia, By Pass Ngurah Rai Street No. 67, Sanur Kaja, South Denpasar, Denpasar City, Bali 80227, Indonesia
[3]Verschuren Centre for Sustainability in Energy and the Environment, Cape Breton University, 1250 Grand Lake Rd, Sydney, Nova Scotia B1P 6L2, Canada

ABSTRACT
Kappaphycus and *Eucheuma*, known collectively as 'eucheumatoids', are two related genera of red seaweeds which currently lead the rankings for volume of global production of farmed macroalgae. Since 2009, the combined cultivated volume of these carrageenophytes overtook that of the brown seaweeds *Laminaria* (*Saccharina*) and *Undaria* for global production tonnages, according to statistics of the Food and Agriculture Organization of the United Nations (FAO). The Southeast Asian region, particularly Indonesia, the Philippines, Malaysia, Tanzania, and East Africa are the major producers of eucheumatoid biomass. Despite several success stories of red seaweed cultivation and the economic and socioeconomic value of their ecosystem services, there remain a number of salutary lessons to be learned from 'agronomic' practices applicable to their extensive cultivation. These case studies should be further developed, analysed, and adopted as best-practice recommendations for future socioeconomic prosperity, as well as both economic and environmental sustainability. In this review, we propose the use of the term 'phyconomy' (i.e. large-scale production of marine macroalgae for economic and industrial purposes) as an alternative to the term agronomy (i.e. terrestrial plant production).

ARTICLE HISTORY
Received 26 May 2018
Accepted 28 May 2019
Published online 11 September 2019

KEYWORDS
Eucheumatoid farming; Phyconomy; Sustainability

INTRODUCTION

The term 'phyconomy' is hereby coined to describe a general concept that embraces large-scale, sustainable seaweed farming for economic benefit in coastal waters. Phyconomic lessons learned from the successful mass cultivation of red seaweeds are guidelines which can be applied to technology transfer and capacity building for other forms of commercial marine macroalgal production. A number of important phyconomic issues are highlighted in this article. They are listed in brief immediately below and will be presented later in greater detail. These issues include the following:

(1) There are a number of important lessons to be learned from the use of repeated vegetative propagation of biomass of *Kappaphycus alvarezii* (Doty) Doty and its long-term production as a monocrop via extensive surface cultivation methods. These practices resulted in low genetic variation and loss of strain vigour which has further ramifications in that the biomass became susceptible pathogens, diseases and epi- or endophyte infestations.
(2) Lack of development in commercial utilisation of local seaweed biodiversity led to seemingly unnecessary introductions of nonindigenous eucheumatoids and their unfettered expansion into new farming areas. Some of these introductions have caused serious environmental issues as invasive organisms; however, the scale of perturbations is debatable.
(3) Failure to innovate new techniques of eucheumatoid farming and indigenous utilisation of raw materials merely fuelled expansion of commercial operations through the unregulated transfer of seedlings to new farming areas to meet increasing global demands.
(4) After expansion of operations, many current tropical carrageenophyte farming efforts are still dependent on rudimentary, labour-intensive technologies, i.e. 'drudge' labour used to tie cuttings onto lines, and the labour required for harvest.
(5) Use of plastic attachments (i.e. tie-ties; TTs) for hanging seedlings on cultivation lines contributes to plastic pollution in the oceans. There are also costs associated with their removal during processing.
(6) There is considerable promise with the recently introduced tubular net, especially as practised by innovative farmers in Brazil, Indonesia and India.
(7) Given the potential value of the crops, there seems to be stagnation in the innovation of eucheumatoid seaweed cultivation as a whole. There is considerable need for additional research and development and investment (commercialisation) for production of

CONTACT Anicia Q. Hurtado anicia.hurtado@gmail.com
Colour versions of one or more of the figures in the article can be found online at www.tandfonline.com/uphy.

eucheumatoid biomass by the carrageenan industry, which still focus largely on the rheological properties of gels for processed food applications.

(8) It is encouraging that multistream zero effluent production and processing techniques are gaining ground in India and Indonesia.

A shift in innovation from simple cultivation methods to a more technical phyconomic approach for eucheumatoids is imperative in order to sustain positive outcomes, such as:

(1) enhancement of human resource capacity;
(2) diversified livelihoods;
(3) adoption of sound, ecosystem-based management principles;
(4) sustainability of operations, including resiliency to climate change; and
(5) secured environmental and crop sustainability and global food security.

Inasmuch as the above issues are lessons for carrageenophyte production, the same phyconomic principles apply to large-scale cultivation of other common seaweed crops e.g. *Porphyra*/*Pyropia*, *Laminaria*/*Saccharina* and *Undaria* (see Hwang *et al.* 2019).

PHYCONOMIC LESSONS TO BE LEARNED AND TRANSFERRED FROM EUCHEUMATOID FARMING

Eucheumatoid farming – that is, farming of *Kappaphycus* spp./strains and varieties and, in particular, *Eucheuma denticulatum* (N.L.Burman) Collins & Hervey – has been practised commercially in the Philippines, the origin of such activities, since 1970 (Doty 1973; Doty & Alvarez 1975; Parker 1974). Such activities expanded rapidly and over a wide geographic range. Now, more than 30 countries are involved in the production of marine crops. These have been so successful collectively that the dried, raw material biomass has become commoditised (Hayashi *et al.* 2017). Tens of thousands of fishers living in coastal communities, often in economically deprived areas, are engaged in seaweed farming. This is often the case in Southeast Asia, notably the Philippines, Indonesia and Malaysia and, to a lesser extent, in Vietnam, Cambodia and Myanmar, and in eastern Africa; for example, Tanzania. The number of individuals involved in farming carrageenan-containing seaweeds globally is somewhat of a conjecture, sometimes exaggerated to be in the millions. We believe that number is more likely to be tens of thousands of family units of varying size. The socioeconomic benefits would therefore be derived by a larger number of people and there would be knock-on economic benefits derived from the goods and services being purchased or traded in the coastal economies for the consumable required (e.g. wood, PVC, string, boats, fuel, etc.). In addition, some of the derived income is commonly used to fund upgrades to transportation, education and healthcare infrastructure and services. Seaweed farming has brought tremendous socioeconomic returns for some seaweed farming communities, and these should be held up as examples worth emulating (for further details and positive 'return on investment', socioeconomic assessments, see Alih 1990; Doty 1986; Firdausy & Tisdell 1991; Hurtado *et al.* 1996, 2001; Samonte 2017; Samonte *et al.* 1990; Smith 1986; Smith & Pestaño-Smith 1980; Valderrama *et al.* 2013).

Despite many challenges, there have been several success stories on phyconomy of eucheumatoids since its inception almost 50 years ago. However, too many overhyped and overly optimistic stories have led to unfettered and unwarranted expansion of eucheumatoid farming to new geographic areas, rather than focusing on local species and strains as cultivars and/or adapting operations to specific local conditions. Below is a list of the most important phyconomic lessons learned. These can be further improved, thereby maximising environmental and economic benefits from eucheumatoid phyconomic activities. As with terrestrial agronomy, marine phyconomy is an ever-evolving practice which becomes a true art as practised by the farmer. It is often said that the farmer's best tool is his shadow, as in constant vigilance and attention to crops. This is well illustrated in the preface to the Cebu International Seaweed Symposium, which includes a photograph of Professor Maxwell Doty examining new seedlings in the field.

RELIANCE ON THE USE OF REPEATED VEGETATIVE PROPAGULES

Vegetative seaweed propagation refers to the process of asexual reproduction whereby a fragment of a parent thallus (i.e. a cutting) is taken (broken off) or cut in order to produce material for the next cycle of cultivation. Essentially, this is a form of in-field selection of thalli by farmers based on size and/or colour, deemed best suited to particular sites. These fragments, known as cuttings, 'seedlings' or propagules, can grow into mature plants over a cycle of 30, 45 or 60 days depending on site or financial needs of growers. Usually, a piece of thallus weighing a kilogramme or more can be split into six to eight cuttings of *c.* 150 g each which then serve as starters in a new cultivation cycle. There are many different colour morphotypes of eucheumatoids (see Hayashi *et al.* 2017) used in commercial cultivation.

It is our view that there was insufficient effort applied to selecting new indigenous cultivars. If more effort had been put into this initially – for example, by sponsored government or industry research – it would not have been necessary to disperse cultivation activities beyond the Philippines. As a consequence, the high costs of shipping and relative cost of the cultivars would have been avoided.

From the start of commercial cultivation of eucheumatoids in 1970, repeated vegetative propagation has also been practised elsewhere in the world. Often, initial stocks were as little as a few kilogrammes, rapidly relocated (shipped by air in coolers), so that selection of materials for new, remote areas was from an extremely limited genetic base.

Earlier studies reported propagule production from spores (Azanza-Corrales & Aliaza 1999; Azanza-Corrales & Ask 2003; Bulboa *et al.* 2007, 2008; Luhan & Sollesta 2010; Roleda *et al.* 2017) and from newly established micropropagation techniques for cultivation purposes; for example, tissue culture (Ali *et al.* 2018a; Dawes & Koch 1991; Dawes *et al.* 1994, 1993; Hayashi *et al.* 2008; Hurtado & Biter 2007; Hurtado & Cheney 2003;

Hurtado *et al.* 2009; Luhan & Mateo 2017; Neves *et al.* 2015; Reddy *et al.* 2003; Sulistiani *et al.* 2012; Tibubos *et al.* 2017; Yeong *et al.* 2014; Yong *et al.* 2014, 2015; Yunque *et al.* 2011; Zitta *et al.* 2013). Because of the technical sophistication required, these were neither embraced by farmers nor, perhaps surprising, sponsored by the very industry which was dependent on generation of the raw materials for processing. Hopefully, this situation is set to change (see also the Red Seaweed Promise project for the sustainable supply of raw materials for Cargill; https://www.cargill.com/sustainability/sustainable-seaweed, accessed 05/04/2019). There are now a few small demonstration farms using propagules generated from micropropagation techniques in a few areas of the Philippines (Capacio, personal communication; Luhan, personal communication); Malaysia (Ali, personal communication) and Vietnam (N. Tran, personal communication). However, these need to be scaled up and appropriately sized to meet future production needs of the global industry. The success of such techniques could be similar to the findings of Gupta *et al.* (2018) using enzymes for the production of protoplasts (i.e. single-celled initials which become seedlings) in *Ulva* sp. that provided a fivefold improvement, without compromising protoplast yield and viability. The phyconomy of eucheumatoids should be dramatically improved by transferring the technology used in *Ulva* sp. cultivation.

The continued use of repeated, vegetative propagules (without sexual union of gametes) and virtual monocropping (without fallow periods) for the commercial cultivation of eucheumatoids led to the loss of strain vigour by the most commonly farmed seaweed cultivars (see Hayashi *et al.* 2017). This subsequently led to susceptibility of the seaweeds to microbial pathogens, which in turn led to crop diseases and pest infestations.

SUSCEPTIBILITY TO DISEASE AND EPIPHYTE INFESTATIONS

Disease in eucheumatoids appeared as abnormal changes in form, physiology, integrity and/or behaviour of the seaweeds. These were direct responses to abiotic stresses such as cultivation close to the water surface and monocropping. A seaweed is considered diseased when it is continuously disturbed by biotic stresses in the form of causal agents which result in abnormal physiological processes that disrupt the normal form and structure, growth, and performance of plants, including reproductive success. There are five levels of pathological responses in eucheumatoids:

(1) Normal physiological functions of the seaweed are disturbed when affected by pathogenic organisms and or environmental factors (i.e. pH, surface seawater temperatures [SST], irradiance/UV exposure).
(2) Initially, seaweed defence mechanisms respond physiologically (i.e. evolution of hydrogen peroxide) to the presence of disease-causing agents, particularly at the site of infection.
(3) The responses then become more widespread and histological changes may take place near the infection site (e.g. the presence of 'goosebumps').
(4) Changes are expressed as symptoms of a known disease which can be visualised macroscopically.
(5) As a consequence of the pathology, seaweed growth is reduced, phycocolloid quality declines, or the infected seaweed may die or be lost from the cultivation site due to fragmentation of the thallus.

The traditional extensive approaches to *Kappaphycus* and *Eucheuma* cultivation exposed plants to many biological and environmental elements which could promote or hinder their growth and development. The earliest 'disease' identified in *Kappaphycus* and *Eucheuma* was 'ice-ice' (Uyengco *et al.* 1981). This was first described as an onset of limited greening of a segment of thallus, followed by a clearly green segment the next day. After a few more days, the infected tissues became very pale and finally entirely bleached or 'whitened' (hence alike to 'ice', from which the term was coined). The infected segments could remain attached for a day or two but soon broke away and disintegrated, separating adjacent parts of the thallus, which appear otherwise unaffected/uninfected. Carrageenophyte farmers became familiar with this 'disease' and developed indigenous knowledge of what to do in cases of an outbreak. Normally, they cut off the affected segments and let the seemingly unaffected thallus continue to regenerate and regrow, albeit with reduced overall productivity. Reports of 'ice-ice disease' in *Kappaphycus* and *Eucheuma* include Largo *et al.* (1995a, 1995b), Mtolera *et al.* (1996), Pedersén *et al.* (1996), Butardo *et al.* (2003), and Achmad *et al.* (2016). The involvement of a marine-derived fungus as the potential causative agent of ice-ice disease in *K. alvarezii* and *K. striatus* was reported by Solis *et al.* (2010).

As early as 2002, a more severe problem in tropical carrageenophyte farming was identified as 'epiphytic' *Polysiphonia*/*Neosiphonia* infestations (Largo 2002) from the Calaguas Islands, Camarines Norte, Philippines. The same problem was observed in Tawi-Tawi seaweed farms as early as 1976 (Hurtado 2005). Unfortunately, at that time, neither the farmers nor the colloid industry considered it a major problem to be addressed. Had investments been made earlier, perhaps the current scenario facing eucheumatoids would be very different. Instead of addressing the issues of marine pests in an integrated phyconomic manner (Ingle *et al.* 2018), as done in terrestrial agronomy, it was 'easier' to expand the areas of farming sites. *Polysiphonia* and *Neosiphonia* are red epiphytic filamentous algae (Ask & Azanza 2002) which can penetrate deeply into the cortex of host tissues by rhizoids, reaching the medullary tissue. As a consequence, the epiphytic filamentous algae destroy host cells in the area around the infection site (Leonardi *et al.* 2006). In response, the host tissues change their morphology to the epi-/endophyte to form cavities, which further weakens the integrity of the tissues, and thalli fragment at the infection sites.

Several later reports recorded *Polysiphonia*/*Neosiphonia* infestations occurring in additional regions of the Philippines and other Southeast Asian countries (Critchley *et al.* 2004; Hurtado *et al.* 2006; Vairappan 2006; Vairappan *et al.* 2008), China (Pang *et al.* 2012, 2015), and Madagascar (Ateweberhan *et al.* 2015; Tsiresy *et al.* 2016). The root cause of this widespread problem was likely that seemingly uninfected, otherwise 'healthy' seedlings were widely traded and dispersed commercially. These had unseen endophytic remnants of the polysiphonous red seaweed hitch-hikers. We hypothesise that the epiphytes originated from unattached *Sargassum* spp.

(Yamamoto *et al.* 2012) drifting on the surface, that had resident epiphytic *Neosiphonia* and *Polysiphonia* spp. which subsequently became entangled with the *Kappaphycus* tied to ropes near or at the surface within the farms. Clearly, the situation was not under control, and the negative impacts of these polysiphonous, endogenous hitch-hikers were unwittingly and easily spread from one region to another within traded and dispersed infected seed stocks. The practice was in part encouraged due to severe shortages of seedlings, because of lack of investment and innovation by industry and farmers.

Ice-ice disease and epi-/endophyte infestation were the direct result of low genetic variability amongst the common cultivars or strains of *K. alvarezii* and *K. striatus* (F.Schmitz) Doty *ex* P.C.Silva (Halling *et al.* 2013). In effect, most farmers had been using the same limited strain stock for almost 47 years, with only vegetative propagation. Over this period, global production went from 1000 metric ton fresh weight (mt fwt) in the 1970s to 11.95 million mt fwt in 2015, and is conservatively projected to be 15 million mt fwt in 2020 (Food and Agriculture Organization of the United Nations [FAO] 2017).

Production of propagules of eucheumatoids produced from spores has not yet been adopted for commercial cultivation. This compares unfavourably to investments made in the commercial cultivation of cultivated seaweeds such as *Hizikia* (Pang *et al.* 2005, 2006), *Ecklonia* (Hwang *et al.* 2009), *Palmaria* (Pang & Lüning 2006), *Pyropia* (Kim *et al.* 2016), *Saccharina* (Li *et al.* 2016), *Sargassum* (Hwang *et al.* 2006; Pang *et al.* 2009) and *Undaria* (Hwang *et al.* 2011, 2014) which have variously produced gametophytes and sporophytes for seedlings, as developed from sexual or asexually derived spores (i.e. meio- or mitospores). An understanding of basic seaweed reproduction is a prerequisite to the success of such innovations in other areas of phyconomic practice (i.e. nori and kelps).

Gachon (2017) described several strategies which could be applied to control marine plant diseases: (1) nutritional intervention; that is, making the host 'stronger' (i.e. increasing vigour) through administration of a biostimulant/bioeffector (van Oosten *et al.* 2017) or a fertiliser dip administered as a preoutplanting soak; (2) breeding disease-resistant algal varieties; and (3) challenging and countering the pathogen with microorganisms 'friendly' to the host. All of these phyconomic intervention strategies have direct parallels to land-based agronomic practices (i.e. use of seed treatments, breeding and selecting productive cultivars, production of hybrid plants, applications of fertilisers and biostimulants and plant protection agents, etc.). So far, phyconomic interventions have been restricted largely to use of a biostimulant/bioeffector which has been reported as successful in *Kappaphycus* in the Philippines and Malaysia and is discussed below.

Under conditions of multiple abiotic stresses – for example, extreme fluctuations in SST, salinity and pH – *K. alvarezii* releases massive amounts of H_2O_2 into the surrounding seawater. This possibly impairs efficient and immediate responses of pivotal H_2O_2-scavenging activities of catalase and ascorbate peroxidase and can culminate in short-term, exacerbated levels of protein and lipid oxidation (Barros *et al.* 2006). Such responses can reduce resistance of the seaweed to the epi/endophyte *Neosiphonia* spp. and epiphytic *Polysiphonia* spp.

Few studies have been undertaken to mitigate the problems of ice-ice disease and incidences of epi/endophytes in *Kappaphycus*. The reports of Loureiro *et al.* (2009, 2012), Borlongon *et al.* (2011), Hurtado *et al.* (2012), Marroig *et al.* (2016) and Ali *et al.* (2018b) highlight the potentially beneficial application of a seaweed extract biostimulant (i.e. *Ascophyllum* Marine Plant Extract Powder, or AMPEP), manufactured from the temperate, intertidal fucoid *Ascophyllum nodosum* (Linnaeus) Le Jolis. This extract enhanced the vigour and health status of pretreated carrageenophyte thalli; it accelerated growth and pigmentation, and simultaneously conveyed improved tolerance to abiotic and biotic stress factors (i.e. expressing both biostimulant and bioeffector properties). Borlongon *et al.* (2011) showed that dipping (i.e. a preplanting soak) of *Kappaphycus* seedlings in a relatively low concentration of AMPEP (i.e. 0.1 g l^{-1}), coupled with outgrowing the seaweed at 50–75 cm below the water surface, significantly lowered the incidence of a prevailing *Neosiphonia* infestation (i.e. 6%–50%) compared to the undipped control thalli (10%–75%). Loureiro *et al.* (2012) showed that pre-outplanting administration of AMPEP reduced the effects of the surface cleansing oxidative bursts (i.e. production of hydrogen peroxide) which can be negative for both the host and its epiphytes, especially in densely planted monocrop systems. This was confirmed by Marroig *et al.* (2016) and Ali *et al.* (2018b) when a much-reduced incidence of *Neosiphonia* and epibionts was recorded in AMPEP-treated *K. alvarezii*. In essence, the treated seaweed tissues acquired properties of improved resistance to biotic stresses (as created by the endophytic *Neosiphonia* spp.). Because AMPEP provides enhanced tolerance to biotic stresses, AMPEP may be considered a bioeffector [as opposed to a biostimulant; see van Oosten *et al.* (2017) for a review].

Luhan *et al.* (2015) showed that a short-term immersion of *Kappaphycus alvarezii* in a high-nitrogen-containing medium, applied before outplanting, increased growth, improved the quality of the carrageenan and, more important, decreased the occurrence of ice-ice disease. Thus, it seems that these varied preplanting procedures primed the eucheumatoids and/or enhanced their immunity to reduce the negative impacts of the epi-/endophytic pathogens.

The susceptibility of farmed eucheumatoids to disease and pest infestations might be due to their low genetic diversity, as claimed by Halling *et al.* (2013) and Zuccarello *et al.* (2006). However, Lim *et al.* (2014) showed that there was higher species diversity in Southeast Asia. This is where many potentially valuable carrageenophyte species occur that were previously overlooked for cultivation because of their morphological plasticity and cryptic nature. Dumilag *et al.* (2016) also repeated a high haplotypic diversity of farmed *Kappaphycus* in the Philippines.

The above-cited strategies using seaweed extracts and nitrogen fertilisation in the pre-outplanting stage are some of the tools adopted to reduce the incidence of disease and pest infestations. Likewise, a framework for marine integrated pest management in seaweed farming, as proposed by Ingle *et al.* (2018), should be seriously considered for adoption. Cottier-Cook *et al.* (2016) emphasised 'characterization, conservation and exploitation of algal genetic resources towards crop improvement, which also includes cost-efficient, noninvasive, parallelised growth measurement; and bioassays to test for pathogen resistance' as a primary future direction. Such an approach would be a major strategy in safeguarding the sustainability of red seaweed phyconomic activities in developing countries (Cottier-Cook *et al.* 2016). It is expected that this much-needed phyconomic initiative will produce relevant research outcomes and commercial developments.

INTRODUCTION OF NONINDIGENOUS EUCHEUMATOIDS INTO NEW FARMING AREAS

The relative ease, without major investments, and the success of *Kappaphycus* and *Eucheuma* phyconomy in the Philippines in the early 1970s (Doty 1973; Doty & Alvarez 1981; Ricohermoso & Deveau 1979, and in Indonesia in the late 1980s, has been remarkable. This led rapidly to the somewhat indiscriminate introduction of these genera to many other countries with suitable subtropical-to-tropical coastal marine environments.

Of the almost 30 countries where these seaweeds were introduced (Ask *et al.* 2003; Hurtado *et al.* 2016), only Kane'ohe Bay, Hawai'i and India have reported bioinvasion issues caused by released fragments from cultivation sites and their re-attachment to corals. The introduction of strains and cultivars of *K. alvarezii*, in particular *K. striatus* and *E. denticulatum*, to areas outside their natural geographic range was with the best of intentions. Considerations included research and evaluation, further commercial cultivation and socioeconomic development of impoverished coastal communities. These were tried-and-trusted strains and species which were known to bring economic gains to seaweed farmers, as well as to the carrageenan industry (Porse & Rudolph 2017).

From 1974 to late 1976, these eucheumatoids were intentionally introduced to the fringing reef surrounding the Hawai'i Institute of Marine Biology at Coconut Island (Moku o Lo'e), Kane'ohe Bay, O'ahu, Hawaiian Islands, for experimental research, strain selection studies and use in commercial aquaculture projects (Doty 1978; Russell 1983). However, these pursuits were ultimately abandoned, which later created problems of biological pollutionas these seaweeds became 'invasive alien species', which then expanded their range and colonised coral reefs by re-attachment through adventitious rhizoids (Conklin & Smith 2005; Rodgers & Cox 1999; Smith *et al.* 2002; Woo 1999). Previously, the re-attachment of eucheumatoids was unknown and not considered a threat when introducing cultivars.

In 2000, *K. alvarezii* (from the Philippines) was introduced by the Indian government's Central Salt and Marine Chemicals Research Institute, in conjunction with PepsiCo, to the Gulf of Mannar Marine Biosphere Reserve, South India, specifically for phyconomic purposes. Five years after its introduction, reports of 'invasive' characteristics were noted (Chandrasekaran *et al.* 2008; Kamalakannan *et al.* 2010; Pereira & Verlecar 2005; Tewari *et al.* 2006). These authors claimed that the lack of functional reproductive material, low spore viability and absence of microscopic phases in the life cycle of eucheumatoids, coupled with the abundance of herbivores, may have limited the spread and success of this alga. However, after much controversy and negative publicity, a bioinvasion by *K. alvarezii* at Kurusadai Island was considered to be a remote possibility; no further issues have been reported. Today, commercial farming of eucheumatoids here and elsewhere in India has contributed to improvements in livelihood of coastal fishers (Krishnan & Narayanakumar 2013; Periyasamy *et al.* 2014a, b, 2015).

Only superficially and endophytically 'clean' postquarantined eucheumatoids should provide the 'seed' stock for any new introduction. Consultation with processors and other producers is recommended to determine which species and variety/strain are most suitable for proposed new locations (for details, refer to Hurtado *et al.* 2016; Sulu *et al.* 2003).

To minimise risks of introducing disease or invasive problems in cultivated seaweeds, stringent quarantine procedures should be adopted whenever cuttings are transferred across international borders or even transplanted domestically to a new location. The reader is referred to quarantine techniques and procedures for seaweeds, and also subsequent successful monitoring programmes for pilot-farming trials in Brazil (de Paula *et al.* 1998; Oliveira *et al.* 1995) and Fiji (Sulu *et al.* 2003).

DEPENDENCE ON RUDIMENTARY, LABOUR-INTENSIVE TECHNOLOGY

Since the introduction of commercial farming of *Kappaphycus* and *Eucheuma* in the Philippines, traditional farming techniques have been extremely tedious and laborious. This included use of stakes and polyethylene rope and soft plastic rope (TT; Fig. 1) or loops (Fig. 2) to tie bunches of seedlings along a supporting line. It is now known that the soft plastic rope used for the TT is not environmentally friendly because it is a source of unwanted plastic both in the ocean and in harvested biomass. Furthermore, its economic life is short because it can be used only once or twice and is not recycled. It is the practice of the farmers, especially those using the multiple-raft longline system, to the harvest by cutting the seaweeds at their point of hanging from the longlines. Thus, a new soft plastic rope (TT) is needed to tie new seedlings onto the line for the next growth cycle. Indonesia and Malaysia adopted the use of soft Kuralon rope (#20) in order to tie the seedlings, either in singlets or in doublets. This type of rope seeding is more environmentally friendly than the soft plastic rope.

A modified raft floating system for *Kappaphycus* using an octagonal raft design which articulates when floating at the surface is currently under trial in India. This is through the auspices of the Council of Scientific and Industrial Research–Central Salt and Marine Chemicals Research Institute, in association with Council of Scientific and Industrial Research–Structural Research Engineering Centre (Hayashi *et al.* 2017). The octagonal design provides a modular structure that is expandable and easy to assemble and anchor. In addition, it provides for the free flow of seawater which replenishes nutrient supply to the plants within the raft area. Good maintenance of the rafts, as well as regular removal of drift seaweed and silt from the seedlings, was more efficient within these structures than with the conventional longline methods. This robust floatation system was also more suitable for anchoring in deeper water which also accessed cooler SST

Fig. 1. Tying of seedlings using plastic tie-tie.

Fig. 2. Tying of seedlings using Kuralon thread loops.

(Hayashi *et al.* 2017). However, this type of growth system for *Kappaphycus* has not yet been commercially adopted.

The introduction of tubular nets (TNs) for growing *Kappaphycus* was first reported by Goes & Reis (2011) in Brazil. Their tubular net was 5 m long with a 20-mm mesh, wherein 20 seedlings (*c.* 100 g each) were positioned (see Neish *et al.* 2017). A PVC tube (1 m long and 75 mm wide) was used as a hopper and was an auxiliary tool to reduce the labour required to load the seedlings into the TN. This PVC tube was a sleeve or hopper for one end of the tubular net, and the seedlings could thereby be fed into the TN, giving a spacing of about 15 cm between each seedling. Both ends of the TN were closed and tied to a 3-m floating PVC pipe. Harvesting consisted of removal of the TN from the raft, which was then cut open to remove and measure seedling growth. Similarly, TNs are presently being used in India for commercial cultivation of *K. alvarezii* (Mantri *et al.* 2017).

In terms of efficiency, Goes & Reis (2011) reported no differences in key performance indicators of daily growth rate and carrageenan yield, or value characteristics such as gel strength and viscosity of *K. alvarezii* grown by either by longlines or by the TN technique. In addition, there was no difference in time required to attach the longline to the raft (second stage). However, significant differences were observed in required time to tie the algal seedlings onto the longline and to fill the TN (first stage), and to harvest seedlings using both techniques (third stage). There was also a significant difference in the element of drudge labour as referred to by Neish *et al.* (2017). The total time required for the TN method was 54% less than for the TT technique. Furthermore, the physical materials consumed by the TN technique cost 20% less than (i.e. 66 m of tubular net and 1 m of PVC tube) than the TT (i.e. 93.5 m of nylon line, 25 m^2 of nylon net and 55 m of polyethylene line). Reis *et al.* (2015) confirmed the efficiency of the TN system for growing *K alvarezii* in Brazil. It was also a desirable technique for adoption in countries where environmental laws were introduced to curb seaweed cultivation. This was the case in Brazil which, until recently, had licenced less than 5% of its available coastline for commercial seaweed cultivation (phyconomic activities; Goes & Reis 2011; Espi *et al.* 2019). TN might also be used in Cuba and Colombia where introduced eucheumatoid seaweeds have been banned from coastal waters for fear that they might escape and become invasive (Hayashi *et al.* 2017). The growth of *K. alvarezii* in TNs in Brazil has now been adopted commercially (Goes & Feder-Martins 2015; Sepulveda 2016).

The above-cited experiences, show that phyconomic methods of extensive seaweed farming are still being developed and refined. These will further enable the simple, effective mechanisation of tasks which previously involved drudge labour, and thereby enabling farmers to increase farm productivity based on return on unit of effort (Neish *et al.* 2017; Vadassery *et al.* 2016). Key features of such systems are:

(1) Biomass is inoculated via a hopper into TNs, rather than by manual fastening onto ropes.
(2) Planting and tending of crops during growth, harvesting and handling are somewhat mechanised using simple machinery that can be operated either on shore or at sea, thus eliminating the most labour-intensive farm chores which were often the tasks of family members, mostly women and children.
(3) Biomass loss caused by frond breakage is virtually eliminated and the impacts of grazers are reduced.
(4) Farming is undertaken within contract farming systems, known as 'outgrower' or 'nucleus-plasma' systems, and managed such that there is traceability and security in the flow of sustainable, fresh, good-quality seaweed biomass to processing facilities on a reliable and predictable daily basis.
(5) The phyconomic principles for eucheumatoids are firmly based on sustainable ecosystem practices, as promoted by the FAO (2010).
(6) Phyconomic systems are updated and specifically designed and engineered to operate in deeper, cooler and more turbulent waters. This contrasts with the original systems in relatively shallow water, and expandsavailable ocean surface that could support successful phyconomic activities.

STAGNATED RESEARCH AND DEVELOPMENT IN THE SEAWEED–CARRAGEENAN INDUSTRY

Research and development stagnated in the carrageenan industry as innovative small to medium enterprises that once dominated the carrageenan business were purchased by large, multinational owners during the late 1970s and into the 1980s. This process coincided with the proliferation of semi-refined carrageenan producers, first in the Philippines and later in Indonesia, China, Chile and Malaysia. Since the advent of semi-refined carrageenan technology, considerable process capacity has been developed based on technology obtained from employees, consultants and equipment suppliers of previously established manufacturers. This process was facilitated by multinational owners of formerly innovative carrageenan enterprises reducing their research spending and farm development activities, and also discharging many senior technical and management staff. In carrageenan value chains, there has been a paucity of innovation leading to new applications and markets for at least two to three decades. The last major new applications were developed about 30 years ago, in the form of iota carrageenan (sourced from *Eucheuma denticulatum*) used in dental products, and kappa carrageenan (sourced from *Kappaphycus* spp.), used in meat processing (Neish & Suryanarayan 2017).

The Philippine carrageenan industry had focussed its efforts on extraction of cultivated seaweed biomass using only single-stream processes. Whilst initially considered to be cost-effective, with good gross margins on products, single-stream processing wastes about 50% of seaweed dry matter and creates high-chloride waste streams. Much of the value of the seaweed biomass that could be recovered and sold as products is simply not captured and wasted unless a multistream, zero-effluent approach (or biorefinery) is adopted (e.g. Zollman *et al.* 2019). The extracted colloids, which can be either a semi-refined or refined carrageenan are used in a diverse range of processed food products but most typically in those that are based on or contain ice cream, meat and poultry, dairy products (including cheese and cream, dairy drinks), non-dairy drinks (e.g. nuts and seeds) and water-based jellies (see Hotchkiss *et al.* 2016). Currently, over 80% of global carrageenan production is utilised by only three major application sectors: (1) processed meats, (2) dairy, and (3) desserts and jellies (Campbell & Hotchkiss 2017; Shannon & Abu-Ghannam 2019).

Neish & Suryanarayan (2017) described the potential of zero-effluent eucheumatoid processing. From their data, the Philippines focused on carrageenan production and, to a lesser extent, the sale of fresh raw materials (as sea vegetables) and dried seaweed. Indonesia initiated research and development on the use of eucheumatoid biomass for biofuels (Fakhrudin *et al.*

2014; Meinita *et al.* 2012). India provided much-needed innovation with the use of eucheumatoid biomass for the manufacture of commercial liquid fertiliser/biostimulant (Eswaran *et al.* 2005) and bioethanol (Khambahty *et al.* 2012; Masarin *et al.* 2016; Neish & Suryanarayan 2017).

Diversifying eucheumatoid seaweed strains and their derived products will ultimately bring more revenue along the whole value chain which, hopefully will soon be embraced in the Philippines. One shining exception is the launch of a new range of products (July 2017) which utilised biomass of *Kappaphycus* spp. for personal care products; for example, shampoo, conditioner, body lotion, facial wash and body soap (N. Morada, personal communication). Such changes are a prerequisite for innovation and development of more product applications for an increasingly demanding global market.

PRINCIPLES OF SEAWEED SUSTAINABILITY AND PHYCONOMIC LESSONS LEARNED FROM THE WORLD OF CARRAGEENOPHYTES

A number of lessons have been learned the hard way over the relatively short history of eucheumatoid farming. It is hoped that this review has outlined the successes and pitfalls which have both favoured and dogged the production of the biomass required as raw materials to feed the global carrageenophyte industry. Paying serious attention to the issues raised may assist other marine phyconomic activities (i.e. avoidance of monocropping and disease incidence) such as nori and kelp production (Kim *et al.* 2014, 2017).

For seaweed farming to be economically and environmentally sustainable, the following should be implemented:

(1) Responsible expansion of farming areas, accompanied by investing in research to improve productivity per unit area.
(2) Productivity improvements through development of enhanced phyconomic practices and wider adoption of existing practices. These include improved quality and diversity of seedling supply, establishment of quarantine regulations, establishment of land–sea-based seedling banks and nurseries, and innovative approaches such as diversified and multitrophic aquaculture. Additional benefits are likely to be derived from annual or bi-annual rotation of seaweed crops and leaving intensive areas of phyconomic activity fallow on a regular basis in tropical to subtropical waters. Crop rotation is a common agricultural practice which should be adopted as a phyconomic tool, but one which would also require more complementary candidate species of for cultivation than currently available. Thus, new candidate seaweed species are urgently required for cultivation.
(3) Increased investment in research, development, innovation and commercial extension is urgently required to meet expected challenges, including disease risks, climate change and further introductions of nonindigenous marine species.

In conclusion, the authors call for stronger collaboration amongst government agencies, academia and the private sector. For further phyconomic conservation and sustainability strategies, please refer to Hurtado (2017), Hayashi *et al.* (2017) and Barbier *et al.* (2019).

ACKNOWLEDGEMENTS

The first author is thankful to GlobalSeaweed for the travel support to attend the 11th IPC at Szczecin, Poland, as a special session speaker. We thank M. Lynn Cornish for constructive comments on an earlier draft and four anonymous reviewers for their insightful and constructive comments.

FUNDING

This article was produced under the umbrella of funding by the GlobalSeaweed project.

REFERENCES

Achmad M., Alimuddin A., Widyastuti U., Sukenda S., Harris E. & Suryanti E. 2016. Molecular identification of new bacterium causing 'ice-ice' diseases on seaweed *Kappaphycus alvarezii*. Paper presented at the Asian-Pacific Aquaculture, Surabaya Indonesia, 26–29 April 2016 (Abstract only).

Alemañ A.E., Robledo D. & Hayashi L. 2019. Development of seaweed cultivation in Latin America: current trends and future prospects. *Phycologia* 58: 462–471. DOI: 10.1080/00318884.2019.1640996.

Ali M.M., Md. Y.S., Critchley A.T. & Hurtado A.Q. 2018b. Impacts of *Ascophyllum* marine plant extract powder (AMPEP) on the growth, incidence of the endophyte *Neosiphonia apiculata* and associated carrageenan quality of three commercial cultivars of *Kappaphycus*. *Journal of Applied Phycology* 30: 1185–1195. DOI: 10.1007/s10811-017-1312-2.

Ali M.M., Sani M.Z.B., Hi K.K., Md. Y.S., Critchley A.T. & Hurtado A.Q. 2018a. The comparative efficiency of a brown algal-derived biostimulant extract (AMPEP), with and without supplemented PGRs: the induction of direct, axis shoots as applied to the propagation of vegetative seedlings for the successful mass cultivation of three commercial strains of *Kappaphycus* in Sabah, Malaysia. *Journal of Applied Phycology* 30: 1913–1919.

Alih E.M. 1990. Economics of seaweed *Eucheuma* farming in Tawi-Tawi Islands in the Philippines. In: *The Second Asian Fisheries Forum* (Ed. by R. Hirano & I. Hanyu), pp. 245–249. Asian Fisheries Society, Manilla, Phillipines.

Ask E.I. & Azanza R.V. 2002. Advances in cultivation technology of commercial eucheumatoid species: a review with suggestion for future research. *Aquaculture* 206: 257–277. DOI: 10.1016/S0044-8486(01)00724-4.

Ask E.I., Batibasaga A., Zertuche-Gonzales J.A. & de San M. 2003. Three decades of *Kappaphycus alvarezii* (Rhodophyta) introduction to non-endemic locations. In: *Proceedings of International Seaweed Symposium 17* (Ed. by A.R.O. Chapman, A.J. Anderson, V.I. Vreeland & I.R. Davidson), pp. 49–57. Oxford University Press, UK.

Ateweberhan M., Rougier A. & Rakotomahazo C. 2015. Influence of environmental factors and farming technique on growth and health of farmed *Kappaphycus alvarezii* (*cottonii*) in southwest Madagascar. *Journal of Applied Phycology* 27: 923–934. DOI: 10.1007/s10811-014-0378-3.

Azanza-Corrales R. & Aliaza T.T. 1999. In vitro carpospore release and germination of *Kappaphycus alvarezii* (Doty) Doty from Tawi-Tawi, Philippines. *Botanica Marina* 42: 281–284.

Azanza-Corrales R. & Ask E. 2003. *Kappaphycus alvarezii* (Doty) Doty carposporeling growth and development in the laboratory. In: *Proceedings of International Seaweed Symposium 17* (Ed. by A.R.O. Chapman, A.J. Anderson, V.I. Vreeland & I.R. Davidson), pp. 95–99. Oxford University Press, UK.

Barbier M., Charrier B., Araujo R., Holdt S.L., Jacquemin B. & Rebours C., Editors. 2019. *PEGASUS - PHYCOMORPH European guidelines for a sustainable aquaculture of seaweeds*, COST Action FA1406 (M. Barbier and B. Charrier, Eds), Roscoff, France https://doi.org/10.21411/2c3w-yc73 .

Barros M.P., Necchi N., JR., Colepicolo P. & Pedersén M. 2006. Kinetic study of the plastoquinone pool availability correlated with H_2O_2 release in seawater and antioxidant responses in the red alga *Kappaphycus alvarezii* exposed to single or combined high light, chilling and chemical stresses. *Biochimica et Biophysica Acta* 1757: 1520–1528. DOI: 10.1016/j.bbabio.2006.06.006.

Borlongon I.A.G., Tibubos K.R., Yunque D.A.T., Hurtado A.Q. & Critchley A.T. 2011. Impact of AMPEP on the growth and occurrence of epiphytic *Neosiphonia* infestation on two varieties of commercially cultivated *Kappaphycus alvarezii* grown at different depths in the Philippines. *Journal of Applied Phycology* 23: 615–621. DOI: 10.1007/s10811-010-9649-9.

Bulboa C., De Paula E.J. & Chow F.Y. 2007. Laboratory germination and sea out-planting of tetraspore progeny from *Kappaphycus striatum* (Rhodophyta) in subtropical waters of Brazil. *Journal of Applied Phycology* 19: 357–363. DOI: 10.1007/s10811-006-9142-7.

Bulboa C., De Paula E.J. & Chow F.Y. 2008. Germination and survival of tetraspores of *Kappaphycus alvarezii* var. *alvarezii* (Solieriaceae, Rhodophyta) introduced in subtropical waters of Brazil. *Phycological Research* 56: 39–45. DOI: 10.1111/pre.2008.56.issue-1.

Butardo V.M., Ganzon-Fortes E.T., Silvestre V., Bacano-Maningas M.B. B., Montaño M.N.E. & Lluisma A.O. 2003. Isolation and classification of culturable bacteria associated with 'ice-ice' disease in *Kappaphycus* and *Eucheuma* (Rhodophyta, Solieriaceae). *Philippine Scientist* 40: 223–2379.

Campbell R. & Hotchkiss S. 2017. Carrageenan industry market overview. In: *Tropical seaweed farming trends, problems and opportunities: focus on spinosum and cottonii of commerce* (Ed. by A.Q. Hurtado, A. T. Critchley & I.C. Neish), pp. 193–206. Springer, Dordrecht, Netherlands.

Chandrasekaran S., Nagendran N.A., Pandiaraja D., Krushnankutty N. & Kamalakannan B. 2008. Bioinvasion of *Kappaphycus alvarezii* on corals in the Gulf of Mannar, India. *Current Science* 94: 1167–1172.

Conklin E.J. & Smith J.E. 2005. Abundance and spread of the invasive red algae, *Kappaphycus* spp., in Kane'ohe Bay, Hawai'i and an experimental assessment of management options. *Biological Invasions* 7: 1029–1039. DOI: 10.1007/s10530-004-3125-x.

Cottier-Cook E.J., Nagabhatla N., Badis Y., Campbell M.L., Chopin T., Dai W., Fang J., He P., Hewitt C.L., Kim G.H. *et al.* 2016. *Safeguarding the future of the global seaweed aquaculture industry*. UNU-INWEH and SAMS, United Kingdom. 12 pp.

Critchley A.T., Largo D.B., Wee W., Bleicher-L'honneur G., Hurtado A.Q. & Shubert J. 2004. A preliminary summary of *Kappaphycus* farming and the impacts of epiphytes. *Japanese Journal of Phycology* 52: 231–232.

Dawes C. & Koch E. 1991. Branch, micropropagule and tissue culture of the red algae *Eucheuma denticulatum* and *Kappaphycus alvarezii* farmed in the Philippines. *Journal of Applied Phycology* 3: 247–257. DOI: 10.1007/BF00003583.

Dawes C.J., Lluisma A.O. & Trono G.C. 1994. Laboratory and field growth studies of commercial strains of *Eucheuma denticulatum* and *Kappaphycus alvarezii* in the Philippines. *Journal of Applied Phycology* 6: 21–24. DOI: 10.1007/BF02185899.

Dawes C.J., Trono G.C., Jr. & Lluisma A.O. 1993. Clonal propagation of *Eucheuma denticulatum* and *Kappaphycus alvarezii* for Philippine seaweed farms. *Hydrobiologia* 260: 379–383. DOI: 10.1007/BF00049044.

Paula E.J., Pereira R.T.L. & Ostini S. 1998. Introdução de espécies exóticas de *Eucheuma* e *Kappaphycus* (Gigartinales, Rhodophyta) para fins de maricultura no litoral brasileiro: abordagem teóricae experimental. In: IV Congresso Latino Americano de Ficologia, IIReunião Ibero-Americana de Ficologia e VII Reunião Brasileira deFicologia (Ed. by E.J. Paula, M. Cordeiro-Marino, D. Pupo Santos, M. Fujii, E.M. Plastino & N. Yokoya), pp. 340–357. Sociedade Brasileira de Ficologia, São Paulo, Brasil..

Doty M.S. 1973. Farming the red seaweed, *Eucheuma*, for carrageenans. *Micronesica* 9: 59–73.

Doty M.S. 1978. *Eucheuma* – current marine agronomy. In: *The marine plant biomass of the Pacific* (Ed. by R. Klauss), pp. 203–214. Oregon State University Press, Corvallis, Oregon, USA.

Doty M.S. 1986. Estimating returns from producing *Gracilaria* and *Eucheuma* on line farms. *Monograph in Biology* 4: 45–62.

Doty M.S. & Alvarez V.B. 1975. Status, problems, advances and economics of *Eucheuma* farms. *Marine Technological Society* 9: 30–35.

Doty M.S. & Alvarez V.B. 1981. *Eucheuma* productivity. In: *Proceedings of the International Seaweed Symposium 8* (Ed. by G.E. Fogg & E. I. Jones), pp. 688–691. University College of North Wales, Bangor, Wales.

Dumilag R.V., Orosco F.L. & Lluisma A.O. 2016. Genetic diversity of *Kappaphycus* species (Gigartinales, Rhodophyta) in the Philippines. *Systematics and Biodiversity* 14(441): 451. DOI: 10.1080/14772000.2016.1157643.

Eswaran K., Ghosh P.K., Siddhanta A.K., Patolia J.S., Perisamy C., Mehta A.S., Mody K.H., Ramayat B.K., Prasad K., Rajyagaguru M.R. *et al.* 2005. Integrated method for production of carrageenan and liquid seaweed fertilizer from fresh seaweeds. *US Patent No. 6,893,479*.

Fakhrudin J., Setyaningish D. & Rahayuningsih M. 2014. Bioethanol production from seaweed *Eucheuma cottonii* by neutralization and detoxification of acidic catalyzed hydrolysate. *International Journal of Environmental Science and Development* 5: 455–458. DOI: 10.7763/IJESD.2014.V5.526.

Firdausy C. & Tisdell C. 1991. Economic returns from seaweed *Eucheuma cottonii* farming in Bali, Indonesia. *Asian Fisheries Science* 4: 61–73.

Food and Agriculture Organization of the United Nations (FAO). 2010. Aquaculture development. 4. Ecosystem approach to aquaculture. *FAO Technical Guidelines for Responsible Fisheries* 5(4) Rome, FAO: 53.

Food and Agriculture Organization of the United Nations (FAO). 2017. Fishery and aquaculture statistics. Global aquaculture production 1950-2015. In: *Fisheries and aquaculture department* [online] (Ed. by J. Fishstat), Rome, Italy. www.fao.org/fishery/statistics/software/fishstatj/en; Updated 2017.

Gachon C. 2017. Novel strategies for preventing diseases in cultivated seaweeds. Plenary paper presented at the 6th Congress of the International Society for Applied Phycology. Nantes, France, 18-23 June.

Goes H. & Feder-Martins A. 2015. Manual para cultivo de carraginotas no Brasil. Online PDF manual by Algasbras Biorre Naria Ltda. http://www.carragenabrasil.com.br; April, 2017.

Goes H.G. & Reis R.P. 2011. An initial comparison of tubular netting versus *tie–tie* methods of cultivation for *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae) on the south coast of Rio de Janeiro State, Brazil. *Journal of Applied Phycology* 23: 607–613. DOI: 10.1007/s10811-010-9647-y.

Gupta V., Trivedi N., Simoni S. & Reddy C.R.K. 2018. Marine macroalgal nursery: A model for sustainable production of seedlings for large scale farming. *Algal Research* 31: 463–468. DOI: 10.1016/j.algal.2018.02.032.

Halling C., Wikströms A., Lilieskö1d-Jöö G., Mörk E., Lundsør E. & Zuccarello G.C. 2013. Introduction of Asian strains and low genetic variation in farmed seaweeds: indications for new management practices. *Journal of Applied Phycology* 25: 89–95. DOI: 10.1007/s10811-012-9842-0.

Hayashi L., Reis R.P., Alves De Los Santos A.A., Castelar B., Robledo D., De Vega G.B., Msuya F.E., Eswaran K., Yasir S., Ali M.J. *et al.* 2017. The cultivation of *Kappaphycus* and *Eucheuma* in tropical and subtropical waters. In: *Tropical seaweed farming trends, problems and opportunities: focus on Spinosum and Cottonii of commerce* (Ed. by A.Q. Hurtado, A.T. Critchley & I.C. Neish), pp. 55–90. Springer, Netherlands.

Hayashi L., Yokoya N.S., Kikuchi D.M. & Oliveira E.C. 2008. Callus induction and micro-propagation improved by colchicine and phytoregulators in *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae). *Journal of Applied Phycology* 20: 653–659. DOI: 10.1007/s10811-007-9234-z.

Hotchkiss S., Brooks M., Campbell R. & Philip K.; Triusa. 2016. The use of carrageenan in food. In: *Carrageenans: sources and extraction methods, molecular structure, bioactive properties and health effects* (Ed. by L. Pereira), pp. 120–130. Nova Science Publications, Hauppauge, New York, USA.

Hurtado A.Q. 2005. Effect of epiphytes on the productivity of *Kappaphycus*: impact of diseases on the economics of producing and processing *Kappaphycus*. Terminal report submitted to Degussa Texturant system (now Cargill Texturizing Solutions), France.

Hurtado A.Q. 2017. *Genetic resources for farmed seaweeds*. Sub-Committee on Aquaculture. Food and Agriculture Organization of the United Nations (FAO) Report. COFI:AQ/IX/2017/SBD.6. 75 pp.

Hurtado A.Q., Agbayani R.F., Sanares R. & De Castro-Mallare M.T.R. 2001. The seasonality and economic feasibility of cultivating *Kappaphycus alvarezii* in Panagatan Cays, Caluya, Antique, Philippines. *Aquaculture* 199: 295–310. DOI: 10.1016/S0044-8486(00)00553-6.

Hurtado A.Q. & Biter A. 2007. Plantlet regeneration of *Kappaphycus alvarezii* var. adik-adik by tissue culture. *Journal of Applied Phycology* 19: 783–786. DOI: 10.1007/s10811-007-9269-1.

Hurtado A.Q. & Cheney D.P. 2003. Propagule production of *Eucheuma denticulatum* (Burman) Collins *et* Harvey by tissue culture. *Botanica Marina* 46: 338–341. DOI: 10.1515/BOT.2003.031.

Hurtado A.Q., Critchley A., Trespoey A. & Bleicher L'honnuer G. 2006. Occurrence of *Polysiphonia* epiphytes in *Kappaphycus* farms at Calaguas Is., Camarines Norte, Philippines. *Journal of Applied Phycology* 18: 301–306. DOI: 10.1007/s10811-006-9032-z.

Hurtado A.Q., Joe M., Sanares R.C., Fan D., Prithiviraj B. & Critchley A. T. 2012. Investigation of the application of Acadian marine plant extract powder (AMPEP) to enhance the growth, phenolic content, free radical scavenging, and iron chelating activities of *Kappaphycus* Doty (Solieriaceae, Gigartinales, Rhodophyta). *Journal of Applied Phycology* 24: 601–611. DOI: 10.1007/s10811-011-9785-x.

Hurtado A.Q., Lim P.E., Tan J., Phang S.M., Neish I.C. & Critchley A.T. 2016. Biodiversity and biogeography of commercial tropical carrageenophytes in the Southeast Asian Region. *Carrageenans: sources and extraction methods, molecular structure, bioactive properties and health effects* (Ed. by L. Pereira), pp. 67–90. Nova Science Publishers, New York, NY, USA.

Hurtado A.Q., Yunque D.A., Tibubos K. & Critchley A.T. 2009. Use of Acadian marine plant extract powder from *Ascophyllum nodosum* in tissue culture of *Kappaphycus* varieties. *Journal of Applied Phycology* 21: 633–639. DOI: 10.1007/s10811-008-9395-4.

Hurtado-Ponce A.Q., Agbayani R.F. & Chavoso E.A.J. 1996. Economics of cultivating *Kappaphycus alvarezii* using fixed-bottom line and hanging-long line methods in Panagatan Cays, Caluya, Antique, Philippines. *Journal of Applied Phycology* 105: 105–109. DOI: 10.1007/BF02186312.

Hwang E.K., Baek J.M. & Park C.S. 2009. The mass cultivation of *Ecklonia stolonifera* Okamura as a summer feed for the abalone industry in Korea. *Journal of Applied Phycology* 21: 585–590. DOI: 10.1007/s10811-009-9402-4.

Hwang E.K., Yotsukura N., Pang S.J., Su L. & Shan T.F. 2019. Seaweed breeding programs and progress in eastern Asian countries. *Phycologia* 58: 484–495. DOI: 10.1080/00318884.2019.1639436.

Hwang E.K., Gong Y.G. & Park C.S. 2011. Cultivation of a brown alga, *Undariopsis peterseniana* (Kjellman) Miyabe *et* Okamura, as a warm temperature species by artificial seed production in Korea. *Journal of Applied Phycology* 23: 449–455. DOI: 10.1007/s10811-010-9598-3.

Hwang E.K., Hwang I.K., Park E.J., Gong Y.G. & Park C.S. 2014. Development and cultivation of F2 hybrid between *Undariopsis peterseniana* and *Undaria pinnatifida* for abalone feed and commercial mariculture in Korea. *Journal of Applied Phycology* 26: 747–752. DOI: 10.1007/s10811-013-0164-7.

Hwang E.K., Park E.J. & Baek J.M. 2006. Artificial seed production and cultivation of the edible brown alga, *Sargassum fulvellum* (Turner) C. Agardh: developing a new species for seaweed cultivation in Korea. *Journal of Applied Phycology* 18: 251–257. DOI: 10.1007/s10811-006-9021-2.

Ingle K.N., Polikovsky M., Chemodanov A. & Goldberg A. 2018. Marine integrated pest management (MIPM) approach for sustainable seagriculture. *Algal Research* 29: 223–232. DOI: 10.1016/j.algal.2017.11.010.

Kamalakannan B., Jeevamni J.J.J., Nnagendran N.A., Pandiaraja D., Krishnan Kutty N. & Chandrasekaran S. 2010. *Turbinaria* sp. as victims to *Kappaphycus alvarezii* in reefs of Gulf of Mannar, India. *Coral Reefs* 29: 1077. DOI: 10.1007/s00338-010-0684-4.

Khambahty Y., Mody K., Gandhi M.R., Thampy S., Maiti P., Brahmbatt H., Eswaran K. & Ghosh P.K. 2012. *Kappaphycus alvarezii* as a source of bioethanol. *Bioresource Technology* 103: 180–185. DOI: 10.1016/j.biortech.2011.10.015.

Kim H.H., Moon K.-H., Kim J.-Y., Shim J. & Klochkova T.A. 2014. A revaluation of algal diseases in Korean *Pyropia* (*Porphyra*) sea farms and their economic impact. *Algae* 29: 249–265. DOI: 10.4490/algae.2014.29.4.249.

Kim J.K., Park M., Kim Y.D., Minb H., Hwang E.K., Hwang I.K., Park E. J., Yoo H.I., Han T.J., Kim C.H. *et al*. 2016. *Macroalgae cultivation in Korea/Asia with emphasis on emerging technology trends*. Advanced Research Projects Agency - Energy. https://arpa-e.energy.gov/sites/default/files/Kim%20et%20al%20ARPA-E%20%28Seaweed%20Aquaculture%20in%20Korea%20%2802-24-2016%29.pdf; accessed 05 April 2019.

Kim J.-O., Kim W.-S., Jeong H.-N., Choi S.-J., Seo J.-S., Park M.-A. & Oh M.-J. 2017. A survey of epiphytic organisms in cultured kelp *Saccharina japonica* in Korea. *Fisheries and Aquatic Sciences* 20: 1. DOI: 10.1186/s41240-017-0046-z.

Krishnan M. & Narayanakumar R. 2013. Social and economic dimensions of carrageenan seaweed farming in India. *Fisheries and Aquaculture Technical Paper No. 580* (Ed. by D. Valderrama, J. Cai, N. Hishamunda & N. Ridler), pp. 163–185. FAO, Rome, Italy.

Largo D.B. 2002. Recent developments in seaweed diseases. In: *Proceedings of the National Seaweed Planning Workshop August 2–3, 2001* (Ed. by A.Q. Hurtado, N.G. Guanzon Jr., T.R. de Castro-Mallare & M.R.J. Luhan), pp. 35–42. SEAFDEC Aquaculture Department, Tigbauan, Iloilo, Philippines.

Largo D.B., Fukami K. & Nishijima T. 1995a. Occasional pathogenic bacteria promoting ice-ice disease in the carrageenan-producing red algae *Kappaphycus alvarezii* and *Eucheuma denticulatum* (Solieriaceae. Gigartinales, Rhodophyta). *Journal of Applied Phycology* 7: 545–554. DOI: 10.1007/BF00003941.

Largo D.B., Fukami K., Nishijima T. & Ohno M. 1995b. Laboratory-induced development of the ice-ice disease of the farmed red algae *Kappaphycus alvarezii* and *Eucheuma denticulatum* (Solieriaceae, Gigartinales, Rhodophyta). *Journal of Applied Phycology* 7: 539–543. DOI: 10.1007/BF00003940.

Leonardi P.I., Miravalles A.B., Faugeron S., Flores V., Beltran J. & Correa J. 2006. Diversity, phenomenology and epidemiology of epiphytism in farmed *Gracilaria chilensis* (Rhodophyta) in northern Chile. *European Journal of Phycology* 41: 247–257. DOI: 10.1080/09670260600645659.

Li X., Zhang Z., Qu S., Liang G., Sun J., Zhao N., Cui C., Cao Z., Li Y., Pan J. *et al*. 2016. Improving seedless kelp (*Saccharina japonica*) during its domestication by hybridizing gametophytes and seedling-raising from sporophytes. *Scientific Reports* 6: 21255. DOI: 10.1038/srep21255.

Lim P.E., Tan J., Phang S.M., Nikmatullah A., Hong D.D., Sunarpi H. & Hurtado A.Q. 2014. Genetic diversity of *Kappaphycus* Doty and *Eucheuma* J. Agardh (Solieriaceae, Rhodophyta) in Southeast Asia. *Journal of Applied Phycology* 26: 1253–1272. DOI: 10.1007/s10811-013-0197-y.

Loureiro R.R., Reis R.P., Berrogain F.D. & Critchley A.T. 2012. Extract powder from the brown alga *Ascophyllum nodosum* (Linnaeus) Le Jolis (AMPEP): a 'vaccine-like effect on *Kappaphycus alvarezii* (Doty) Doty ex P.C. Silva. *Journal of Applied Phycology* 24: 427–432. DOI: 10.1007/s10811-011-9735-7.

Loureiro R.R., Reis R.P. & Critchley A.T. 2009. *In vitro* cultivation of three *Kappaphycus alvarezii* (Rhodophyta, Areschougiaceae) variants (green, red and brown) exposed to commercial extract of the brown alga *Ascophyllum nodosum* (Fucaceae, Ochrophyta). *Journal of Applied Phycology* 22: 101–104. DOI: 10.1007/s10811-009-9412-2.

Luhan A., Avenceña S.S. & Mateo J.P. 2015. Effect of short-term immersion of *Kappaphycus alvarezii* (Doty) Doty in high nitrogen on the growth, nitrogen assimilation, carrageenan quality, and occurrence of "ice-ice" disease. *Journal of Applied Phycology* 27: 917–922. DOI: 10.1007/s10811-014-0365-8.

Luhan M.R.J. & Mateo J.P. 2017. Clonal production of *Kappaphycus alvarezii* (Doty) Doty in vitro. *Journal of Applied Phycology* 29: 2339–2344. DOI: 10.1007/s10811-017-1105-7.

Luhan M.R.J. & Sollesta H. 2010. Growing the reproductive cells (carpospores) of the seaweed, *Kappaphycus striatum*, in the laboratory until outplanting in the field and maturation to tetrasporophyte. *Journal of Applied Phycology* 22: 579–585. DOI: 10.1007/s10811-009-9497-7.

Mantri V.A., Eswaran K., Shanmugan M., Ganesan M., Veeragurunathan V., Thiruppathi S., Reddy C.R.K. & Seth A. 2017. An appraisal on commercial farming of *Kappaphycus alvarezii* in India: success in diversification of livelihood and prospects. *Journal of Applied Phycology* 29: 335–357. DOI: 10.1007/s10811-016-0948-7.

Marroig R.G., Loureiro R.R. & Reis R.P. 2016. The effect of *Ascophyllum nodosum* (Ochrophyta) extract powder on the epibiosis of *Kappaphycus alvarezii* (Rhodophyta) commercially cultivated on floating rafts. *Journal of Applied Phycology* 28: 2471–2477. DOI: 10.1007/s10811-015-0770-7.

Masarin F., Cedeno F.R.P., Chavez E.G.S., De Oliveira L.E., Gelli V.C. & Monti R. 2016. Chemical analysis and bio refinery of red algae *Kappaphycus alvarezii* for efficient production of glucose from residue of carrageenan extraction process. *Biotechnology Biofuels* 9: 1–12. DOI: 10.1186/s13068-016-0535-9.

Meinita M.D.N., Yong Y.K., Kang G.T., Jeong G.T., Koo H.M. & Park S. M. 2012. Bioethanol production from the acid hydrolysate of the carrageenophyte *Kappaphycus alvarezii* (cottonii). *Journal of Applied Phycology* 24: 857–862. DOI: 10.1007/s10811-011-9705-0.

Mtolera M.S.P., Collén J., Pedersén M., Ekdahl A., Abrahamsson K. & Semesi A.K. 1996. Stress-induced production of volatile halogenated organic compounds in *Eucheuma denticulatum* (Rhodophyta) caused by elevated pH and high light intensities. *European Journal of Phycology* 31: 89–95. DOI: 10.1080/09670269600651241.

Neish I.C., Sepulveda M., Hurtado A.Q. & Critchley A.T. 2017. Reflections on the commercial development of eucheumatoid seaweed farming. In: *Tropical seaweed farming trends, problems and opportunities: focus on Spinosum and Cottonii of commerce* (Ed. by A.Q. Hurtado, A.T. Critchley & I.C. Neish), pp. 1–28. Springer, Netherlands.

Neish I.C. & Suryanarayan S. 2017. Development of eucheumatoid seaweed value-chains through carrageenan and beyond. In: *Tropical seaweed farming trends, problems and opportunities: focus on Spinosum and Cottonii of Commerce* (Ed. by A.Q. Hurtado, A.T. Critchley & I. C. Neish), pp. 173–192. Springer, Netherlands.

Neves F.A.S., Simioni C., Bouzon Z.L. & Hayashi L. 2015. Effects of spindle inhibitors and phytoregulators on the micro-propagation of *Kappaphycus alvarezii* (Rhodophyta, Gigartinales). *Journal of Applied Phycology* 27: 437–445. DOI: 10.1007/s10811-014-0309-3.

Oliveira E.C., Paula E.J., Plastino E.M. & Petti R. 1995. Methodologies para cultivars no axenic de microalga's marinas *in vitro*. In: *Manual de methods biologics* (Ed. by K. Alveal), pp. 429–447. Univ. Concepción, Chile.

Pang S.J., Chen L.T., Zhuang D.G., Fei X.G. & Sun J.Z. 2005. Cultivation of the brown alga *Hizikia fusiformis* (Harvey) Okamura: enhanced seedling production in tumbled culture. *Aquaculture* 245: 321–329. DOI: 10.1016/j.aquaculture.2004.12.011.

Pang S.J., Gao S.Q. & Sun J.Z. 2006. Cultivation of the brown alga *Hizikia fusiformis* (Harvey) Okamura: controlled fertilization and early development of seedlings in raceway tanks in ambient light and temperature. *Journal of Applied Phycology* 18: 723–731. DOI: 10.1007/s10811-006-9078-y.

Pang S.J., Liu F., Shan T.F., Gao S.Q. & Zhang Z.H. 2009. Cultivation of the brown alga *Sargassum horneri*: sexual reproduction and seedling production in tank culture under reduced solar irradiance in ambient temperature. *Journal of Applied Phycology* 21: 413–422. DOI: 10.1007/s10811-008-9386-5.

Pang S.J. & Lüning K. 2006. Tank cultivation of the red alga *Palmaria palmata*: year-round induction of tetrasporangia, tetraspore release in darkness and mass cultivation of vegetative thalli. *Aquaculture* 252: 20–30. DOI: 10.1016/j.aquaculture.2005.11.046.

Pang T., Liu J., Liu Q., Li H. & Li J. 2015. Observations on pests and diseases affecting a eucheumatoid farm in China. *Journal of Applied Phycology* 27: 1975–1984. DOI: 10.1007/s10811-014-0507-z.

Pang T., Liu J., Liu Q., Zhang L. & Lin W. 2012. Impacts of glyphosate on photosynthetic behaviors in *Kappaphycus alvarezii* and *Neosiphonia sabatier* detected by JIP-test. *Journal of Applied Phycology* 24: 467–473. DOI: 10.1007/s10811-012-9796-2.

Parker H.S. 1974. The culture of the red algal genus *Eucheuma* in the Philippines. *Aquaculture* 3: 425–439. DOI: 10.1016/0044-8486(74)90009-X.

Pedersén M., Collén J., Abrahamsson K., Mtolera M., Semesi A. & Garcia-Reina G. 1996. The 'ice–ice' disease and oxidative stress of marine algae. In: *Current trends in marine botanical research in the east African region* (Ed. by M. Bjork, A.K. Semesi, M. Pedersén & B. Bergman), pp. 11–24. Ord & Veranda AB, Uppsala, Sweden.

Pereira N. & Verlecar X.N. 2005. Is Gulf of Mannar heading for marine bio invasion? *Current Science* 89: 1309–1310.

Periyasamy C., Anantharaman P. & Balasubramanian T. 2014a. Social upliftment of coastal fisher women through seaweed (*Kappaphycus* alvarezii (Doty) Doty) farming in Tamil Nadu, India. *Journal of Applied Phycology* 26: 775–781. DOI: 10.1007/s10811-013-0228-8.

Periyasamy C., Anantharaman P. & Subba Rao P.V. 2015. Experimental farming of *Kappaphycus alvarezii* (Doty) Doty with income estimates at different sites in the Mandapam region, Palk Bay, southeast coast of India. *Journal of Applied Phycology* 27: 935–944. DOI: 10.1007/s10811-014-0380-9.

Porse H. & Rudolph B. 2017. The seaweed hydrocolloids industry: 2016 updates, needs and outlook. *Journal of Applied Phycology* 29: 2187–2200. DOI: 10.1007/s10811-017-1144-0.

Reddy C.R.K., Kumar G.R.K., Siddhanta A.K. & Tewari A. 2003. *In vitro* somatic embryogenesis and regeneration of somatic embryos from pigmented callus of *Kappaphycus alvarezii* (Doty) Doty (Rhodophyta, Gigartinales). *Journal of Phycology* 39: 610–616. DOI: 10.1046/j.1529-8817.2003.02092.x.

Reis R.P., Das Chagas P.R. & De Goes H.G. 2015. The efficiency of tubular netting method of cultivation for *Kappaphycus alvarezii* (Rhodophyta, Gigartinales) on the southeastern Brazilian coast. *Journal of Applied Phycology* 27: 421–426. DOI: 10.1007/s10811-014-0330-6.

Ricohermoso M.A. & Deveau L.E. 1979. Review of commercial propagation of *Eucheuma* (Florideophyceae) clones in the Philippines. In: *International Seaweed Symposium 9* (Ed. by A. Jensen & J.R. Stein), pp. 525–531. Science Press, Princeton, New York, USA.

Rodgers S.K. & Cox E.F. 1999. The distributions of the introduced rhodophytes *Kappaphycus alvarezii, Kappaphycus striatum* and *Gracilaria salicornia* in relation to various physical and biological factors in Kane'ohe Bay, O'ahu, Hawai'i. *Pacific Science* 53: 232–241.

Roleda M.Y., Rodrigora-Calala L.D., Hinaloc L.A.R. & Ganzon-Fortes E.T. 2017. Red, blue, and green, and shades in between: plasticity in color expression in the life history of *Kappaphycus*. Poster presentation at the 6th International Society of Applied Phycology Congress, Nantes, France, 18-23 June 2017.

Russell D.J. 1983. Ecology of imported red seaweed *Kappaphycus alvarezii* (*E. striatum* Schmitz) on Coconut Island, Oahu, Hawaii. *Pacific Science* 37: 87–107.

Samonte G.P.B., Hurtado-Ponce A.Q. & Caturao R. 1990. Economic analysis of bottom line and raft monoline culture of *Kappaphycus alvarezii* var. *tambalang* in Western Visayas, Philippines. *Aquaculture* 110: 1–11. DOI: 10.1016/0044-8486(93)90429-3.

Samonte G.P.S. 2017. Economics of *Kappaphycus* spp. seaweed farming with special reference to the Central Philippines. In: *Tropical seaweed farming trends, problems and opportunities: focus on Spinosum and Cottonii of commerce* (Ed. by A. Q. Hurtado, A.T. Critchley & I.C. Neish), pp. 147–154. Springer, Netherlands.

Sepulveda M. 2016. O potencial da maricultura: oferta mundial da macroalga *Kappaphycus alvarezii* cresce para attender demanda por carragena. *Panorama da Aquicultura* 26(153).

Shannon E. & Abu-Ghannam N. 2019. Seaweeds as nutraceuticals for health and nutrition. *Phycologia* 58: 563–577. DOI: 10.1080/00318884.2019.1640533.

Smith I.R. 1986. *The economics of small-scale seaweed production in the South China Sea Region*. Food and Agriculture Organization of the United Nations. *Proceedings of the Indo-Pacific Fishery Commission* 19(3): 715-729 .

Smith I.R. & Pestaño-Smith R. 1980. Seaweed farming as alternative income for small-scale fishermen: a case study. *Proceedings of the Indo-Pacific Fisheries Commission* 19: 715–729.

Smith J.E., Hunter C.L. & Smith C.M. 2002. Distribution and reproductive characteristics of nonindigenous and invasive marine algae in the Hawaiian Islands. *Pacific Science* 56: 299–315. DOI: 10.1353/psc.2002.0030.

Solis M.J.L., Dreager S. & De La Cruz T.E.E. 2010. Marine-derived fungi from *Kappaphycus alvarezii* and *K. striatum* as potential causative agents of '*ice-ice*' disease in farmed seaweeds. *Botanica Marina* 53: 587–594. DOI: 10.1515/bot.2010.071.

Sulistiani E., Soelistyowati D.T. & Alimuddin Y.S.A. 2012. Callus induction and laments regeneration from callus of cottonii seaweed *Kappaphycus alvarezii* (Doty) collected from Natuna Islands, Riau Islands Province. *Biotropia* 19: 103–114.

Sulu R., Kumar L., Hay C. & Pickering T. 2003. *Kappaphycus* seaweed in the Pacific: review of introductions and field testing proposed quarantine protocols. (Aquaculture Technical Papers/Pickering), 2003, ISSN 1683-7568.

Tewari A., Eswaran K., Subba Rao P.V. & Jha B. 2006. Is *Kappaphycus alvarezii* heading towards marine bioinvasion? *Current Science* 90: 619–620.

Tibubos K., Hurtado A.Q. & Critchley A.T. 2017. Direct formation of axes in new plantlets of *Kappaphycus alvarezii* (Doty) Doty, as influenced by the use of AMPEP K^+, spindle inhibitors and plant growth hormones. *Journal of Applied Phycology* 29: 2345–2349. DOI: 10.1007/s10811-016-0988-z.

Tsiresy G., Preux J., Lavitra T., Dubois P., Lepoint G. & Eekhaut I. 2016. Phenology of farmed seaweed *Kappaphycus alvarezii* infestation by the parasitic epiphyte *Polysiphonia* sp. in Madagascar. *Journal of Applied Phycology* 28: 2903–2914. DOI: 10.1007/s10811-016-0813-8.

Uyenco F.R., Saniel L.S. & Jacinto G.S. 1981. The 'ice–ice' problem in seaweed farming. In: *Proceedings of the International Seaweed Symposium* (Ed. by T. Levring), pp. 625–630. De Gruyter, Berlin, Germany.

Vadassery N., Neish I. & Suryanarayan S. 2016. Systems for achieving high productivity during cultivation of *Kappaphycus* and *Eucheuma*. Paper presented at the *22nd International Seaweed Symposium*, Copenhagen, Denmark, 19–24 June 2016.

Vairappan C.S. 2006. Seasonal occurrences of epiphytic algae on the commercially cultivated red alga *Kappaphycus alvarezii* (Solieriaceae, Gigartinales, Rhodophyta). *Journal of Applied Phycology* 18: 611–617. DOI: 10.1007/s10811-006-9062-6.

Vairappan C.S., Chung C.S., Hurtado A.Q., Msuya F., Bleicher-L'honneur G. & Critchley A.T. 2008. Distribution and malaise of epiphyte infection in major carrageenophyte-producing farms. *Journal of Applied Phycology* 20: 477–483. DOI: 10.1007/s10811-007-9299-8.

Valderrama D., Cai J., Hishamunda N. & Ridler N. 2013. Social and economic dimensions of carrageenan seaweed farming. *Fisheries and Aquaculture Technical Paper No. 580*. FAO, Rome, Italy. 216 pp.

van Oosten M.J., Pepe O., De Pascale S., Siletti S. & Maggio A. 2017. The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants. *Chemical and Biological Technologies in Agriculture* 4. DOI: 10.1186/s40538-017-0089-5.

Woo M. 1999. *Ecological impacts and interactions of the introduced red alga* Kappaphycus striatum *in Kaneohe Bay, Oahu*. Master thesis. Department of Botany, University of Hawaii, Honolulu. 100 pp.

Yamamoto K., Yoshikawa S., Ohkil K. & Kamiya M. 2012. Unique distribution of epiphytic *Neosiphonia harveyi* (Rhodomelaceae, Rhodophyta) along sargassacean hosts. *Phycological Research* 60: 70–75. DOI: 10.1111/pre.2012.60.issue-1.

Yeong H.Y., Phang S.M., Reddy C.R.K. & Khalid N. 2014. Production of clonal planting materials from *Gracilaria changii* and *Kappaphycus alvarezii* through tissue culture and airlift photobioreactors. *Journal of Applied Phycology* 26: 729–746. DOI: 10.1007/s10811-013-0122-4.

Yong W.T.L., Ting S.H., Yong Y.S., Thien V.Y., Wong S.H., Chin W.L., Rodrigues K.F. & Anton A. 2014. Optimization of culture conditions for the direct regeneration of *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae). *Journal of Applied Phycology* 26: 1597–1606. DOI: 10.1007/s10811-013-0191-4.

Yong Y.S., Yong W.T.L., Thien V.Y., Ng S.E., Anton A. & Yassir S. 2015. Acclimatization of micropropagated *Kappaphycus alvarezii* (Doty) Doty ex Silva (Rhodophyta, Solieriaceae) in outdoor nursery system. *Journal of Applied Phycology* 27: 413–419. DOI: 10.1007/s10811-014-0289-3.

Yunque D.A., Tibubos K.R., Hurtado A.Q. & Critchley A.T. 2011. Optimization of culture conditions for tissue culture production of young plantlets of carrageenophyte *Kappaphycus*. *Journal of Applied Phycology* 23: 433–438. DOI: 10.1007/s10811-010-9594-7.

Zitta C.S., Rover T., Hayashi L. & Bouzon Z.L. 2013. Callus ontogeny of the *Kappaphycus alvarezii* (Rhodophyta, Gigartinales) brown tetrasporophyte strain. *Journal of Applied Phycology* 25: 615–629. DOI: 10.1007/s10811-012-9896-z.

Zollmann M.,Robin A., Prabhu M., Polikovsky M., Gillis A., Grieserman S. & Golberg A. 2019. Green technology in green macroalgal biorefinery. *Phycologia* 58: 516–534. DOI: 10.1080/00318884.2019.1640516.

Zuccarello G.C., Critchley A.T., Smith J., Sieber V., Bleicher L'honneur G.B. & West J.A. 2006. Systematics and genetic variation in commercial *Kappaphycus* and *Eucheuma* (Solieriaceae, Rhodophyta). *Journal of Applied Phycology* 18(643): 651. DOI: 10.1007/s10811-006-9066-2.